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MODELING OF SEISMIC PHENOMENA

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The purpose of a large part of investigations on the modeling of seismic phenomena is to work out, with the aid of models, the problems posed by the dynamics of seismic waves, which one necessarily encounters in "gross" seismology, during a study of natural earthquakes, and also in experimental seismology and seismic prospecting, in which elastic waves are excited in the earth by means of explosions or other artificial sources of oscillation.

In seismics (seismology, seismic prospecting), the interpretation of observations, until recently, was based mainly on the determinations of the travel time of various elastic waves from a source of mechanical oscillations -- namely, earthquake focus, explosion, or other source of shock -- to seismic receivers connected to devices that record the ground's vibrations at reception points. Here, from the records of seismic oscillations (namely, seismograms), we employed only those points corresponding to the moments of arrival of individual waves -- namely, longitudinal, transverse, and surface waves traversing the intermediate medium along various paths from source to receiver. An analysis of the passage time of the various waves to seismographs disposed at various distances and in various directions from the source permits one to decide on the structure of the medium through which these waves passed and to determine the velocity with which they were propagated in the various regions of the medium and further, to find in the earth, those surfaces from which the waves were reflected or by which they were refracted. Obviously, such surfaces correspond to boundaries of separation between subterranean layers, or between portions of the medium which are characterized by various physical properties.

In the main, it is just this data -- namely, the time of arrival of elastic waves -- that serves in present-day seismics as the basis for conclusions concerning the earth's structure at very diverse depths: from several meters up to even several tens of kilometers during excitation of waves by artificial means and from tens and hundreds of kilometers up to the complete "transparency"

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of the entire terrestrial globe during utilization of waves excited by natural earthquakes. One can demand from seismics, however, more than the determination of just the velocities of propagation of waves and the geometrical distribution of boundaries of separation of layers in the earth. To obtain this data, one utilizes merely the kinematics of the phenomenon, since only the arrival time of waves is noted on the seismograms. If, however, one utilizes also the dynamic peculiarities of the waves -- namely, their predominant amplitudes and periods -- and traces on the seismograms the variations in form of seismic oscillations, then this affords material for obtaining more complete information on the physical properties of the various parts of the medium; for example, on the differences in absorbing capacity of the parts of the medium in relation to elastic energy, which relation is connected with nonideal elasticity, etc. Such information would extend considerably the boundaries of the region under study and the reliability of physical and geological conclusions based on seismic observations.

Attempts to supplement the kinematic methods of analysis of seismic data by dynamic considerations were made quite early. Thus, in seismology, on the basis of more or less relative intensity of surface waves in comparison with waves of other types, we have sometimes succeeded in judging the depth of foci of remote earthquakes according to merely one form or shape of seismograms. This is important, particularly for clarifying the causes governing the occurrence of earthquakes and for finding methods for forecasting them.

Qualitative methods for calculating the dynamic peculiarities of seismic oscillations are employed also in seismic prospecting; for example, for establishing the response of waves recorded on seismograms to definite geologic boundaries. In recent years, methods involving also quantitative use of dynamic peculiarities of waves have been developed in seismic prospecting.

However, the successful future development of these methods is blocked by the absence of sufficiently developed procedures for solving qualitatively, in a complete and operative manner, not only so-called inverse or indirect problems of geophysics in the field concerned with the dynamics of seismic waves (that is, given a dynamic wave picture, one is required to determine the structure of the medium), but also extremely more simple (in principle) and direct problems, known beforehand to be unique, in this field (that is, given the structure of the medium and familiarity with the source of oscillations, one is required to determine the wave picture). A collection of solutions of a number of elementary direct problems would permit one to obtain, under definite limiting conditions, numerical solutions of corresponding inverse (indirect) problems.

One of the simplest direct dynamic problems of seismics -- namely, for a homogeneous elastic (solid) half space with source on a plane-free boundary -- was solved by Academician S. L. Sobolev as early as 1932. Since that time, Soviet mathematicians have obtained solutions for a number of more complicated problems of this type for nonhomogeneous media, but these solutions ordinarily are represented only in general form and often are extremely remote from the possibility of obtaining numerical results and constructing theoretical seismograms. Meanwhile, these results and seismograms would have been practicable for direct comparison with experimental data -- namely, with field seismograms obtained in seismology and seismic prospecting.

Further theoretical works in this direction are being conducted particularly in the mathematical section of the Geophysics Institute, Academy of Sciences USSR, by Professor N. V. Zvolinskiy and by L. P. Zaytsev. These works show that the obtaining of the complete quantitative (numerical, or represented in the form of graphs) solutions of dynamic problems in seismics is a difficult matter requiring in each individual case much time and tremendous computations, which for the most part are far from elementary.

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Such being the position in the field concerned with the solution of dynamic problems of seismics, beside the further, more intensive development of theoretical methods for their solution, the development of experimental methods for solving these problems by way of conducting suitable field and laboratory experiments under strictly controlled conditions on media whose structure is known beforehand assumes special significance.

The experimental solution of such problems under field conditions encounters many difficulties. Chief of these is that even in places with a comparatively well-studied geological structure (for example, in regions with a large number of deep-drilled wells), the physical properties of minerals in the part under investigation ordinarily will be shown insufficiently fully; and the very structure of a natural medium turns out to be too complex for solving this concrete problem. But this difficulty is completely eliminated under laboratory conditions for experiments on specially constructed models of nonhomogeneous media.

All these considerations have resulted in the establishing of work on the modeling of seismic phenomena at the Geophysics Institute, Academy of Sciences USSR. These considerations have determined the direction of the work.

In the modeling of seismic waves, work of a similar trend has never been conducted systematically previously. Therefore, at first it was necessary to find and develop the most rational methods of modeling in seismics; afterward, to investigate on models concrete problems concerning the propagation of elastic waves, which are of interest for seismology and seismic prospecting.

During the solution of the first problem, naturally, it was necessary to proceed from experience with similar work in allied fields of physics and engineering.

Originally, our investigations were directed along the path of a search for network systems. Mechanical arrangements for demonstrating and studying waves, which are based on the principle of an elastic network with inertial elements at the nodes, were first utilized in physical laboratories to demonstrate various wave phenomena from the field of optics and radio engineering. These arrangements were executed in the form of one-dimensional network systems of small links. In the Laboratory for the Modeling of Seismic Phenomena, Geophysics Institute, Academy of Sciences USSR, the author and his young scientific associate, B. N. Ivakin, had investigated theoretically, constructed, and experimented with mechanical one-dimensional and two-dimensional network models.

The two-dimensional model is a plane network consisting of rubber strings (or elastic films) with loads (weights) fastened at the nodes. The size of the loads at different places of the network can be varied, which permits one to create in this medium various kinds of nonhomogeneities of a rough scale; for example, to divide the new work into two "layers" with boundaries of separation of arbitrary form. Elastic waves in the network are excited by a special striker acting on a certain load. The motion of any other load can be described by means of a scheme consisting of a photoelement, amplifier, and oscillograph.

In theoretical works connected with the modeling of waves on network models, we investigated problems concerning the frequency properties of discrete (discontinuous) network systems regarded as media, with a "structural" nonhomogeneity of a fine scale, in contrast with those natural media which can be considered as continuous and uniform. We compared the processes governing the propagation, reflection, and refraction of elastic waves in discrete media and in the corresponding continuous (uniform) media. We studied elastic anisotropy of two-dimensional network of a definite type. Computations were accompanied by experiments on models.

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We are experimentally studying a number of peculiarities in the propagation of impulses in network models: homogeneous and nonhomogeneous, one dimensional and two dimensional. In particular, on a two-layer, two-dimensional model, we verified observations of the main (leading) refracted elastic waves analogous to the leading sound waves caused by a shell moving with supersonic speed. The leading refracted elastic waves suggest waves on water diverging from the bow of a rapidly sailing boat. In optics, this corresponds to the familiar Cherenkov radiation, whose physical explanation was given by Academician S. I. Vavilov. The present-day method of seismic prospecting by refracted waves is based on the recording of such elastic waves.

We are also considering certain phenomena in natural media which are connected with their heterogeneity, "structural" nonhomogeneity similar to the nonhomogeneity of network models. Examples of such natural media are the partial interstratification of limestones and clays, or clays and sands, sand in the upper layers of the ground where the interstices among the sandstones are filled with air, etc. Special attention has been paid to the conditions under which the velocity of propagation of waves in a structural-nonhomogeneous medium turns out, on the whole, to be "supersmall" -- namely, less than the velocity in each of the components of this medium. An example of a natural medium of such a kind is the "zone of disintegration" ("zone of small velocities") which one must ordinarily encounter in seismic prospecting. A network model is an example of such an artificial medium: namely, the velocity of propagation in it of longitudinal elastic waves, also in essence "supersmall," is less than the velocity in rubber, of which the elastic strings are composed, and less than the velocity in metal, of which the loads are made.

Although we succeeded, during operations with network models, in examining certain problems of known interest to seismics, in all, it turned out that arrangements of such a kind possess in practice very limited possibilities for investigations in the main direction -- namely, for the detailed quantitative study of wave phenomena in nonhomogeneous continuous media.

As it turned out, to attain a close correspondence between the phenomena on the model and in nature, it would have been necessary to employ networks with a far larger number of elements than that used in our setup (several hundred). The insufficient thickness (density) of the network causes the small resolving capacity of the model; in this connection, during modeling, we obtained only a rough similarity to pictures of phenomena observed in nature. The increase which is needed in the number of elements for two-dimensional models, of interest to us now, and more so, three-dimensional models, is difficult to effect in practice. Obviously, this concerns not only mechanical networks but also both network systems of other kinds -- for example, L. I. Gutenmakher's type of electrical integrators -- and mathematical approximate-difference methods (corresponding to diverse systems of networks) for numerically solving differential equations of mathematical physics applicable to problems of the character under consideration. Network systems and difference (finite-difference) methods of computation are convenient for describing chiefly stationary regimes (states) in thermodynamics, hydrodynamics, etc, where sufficiently smooth pictures of phenomena, which are devoid of a large number of fine details, are obtained. In seismics, however, these methods turn out to be too rough or too cumbersome in describing the rich details of the nonstationary dynamic pictures of elastic phenomena in three-dimensional nonhomogeneous continuous media.

In this connection, the works of the laboratory have been directed since 1947 along another path -- namely, along the path of modeling elastic waves in continuous media. For media, we had selected such practically continuous (for given scales) substances as metals, cement, glass, plastics, paraffin, fluids, certain natural minerals, etc.

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The difference between model and nature consisted only in the linear dimensions: namely, the dimensions of the models for problems of seismic prospecting were of the order of 1/1,000 of the dimensions in nature; and for problems of seismology, they were still smaller. Since the velocity of occurrence of the studied processes in the media of the model in the natural media remained of one order, the time intervals with which we had to deal in the model were thousands of times less than in nature. If, during seismic prospecting observations, the accuracy of time readings on seismograms is ordinarily around 0.001 second, then, during modeling, it is necessary to reduce this figure to about 10^{-6} second. This circumstance has led to the necessity of employing technical means which differ from those taken in "gross" seismology and seismic prospecting. In essence, only the basic idea of the experimental seismic setup has remained unaffected: namely, the source of oscillations (earthquake focus, explosion, vibrator) causes elastic waves in the medium which are recorded by means of receivers (seismographs). The seismograms are the primary results of model, as well as field, observations.

Despite the difference in technique, the laboratory seismograms possess approximately the same aspect as the field seismograms of present-day multichannel seismic prospecting stations.

To model seismic waves, radio-engineering devices were employed which are similar to those used in ultrasonic hydroacoustics or impulse ultra-acoustic defectoscopy of metal objects.

In the process of operations, this technique was gradually perfected. The scheme developed by B. N. Ivakin and V. R. Bugrov, associates of the laboratory, in 1949-1950 answers the main requirements of modeling and permit one rapidly to conduct sufficiently accurate observations. By means of this scheme, we have studied a number of dynamic problems of seismology and seismic prospecting. In particular, we have conducted certain investigations on the intensity of leading waves, which are used in seismic prospecting according to the method of refracted waves; we carried out observations on the variations in form of a seismogram for increasing depths of earthquake foci, etc. Investigations of this kind are being continued.

The setup developed in the laboratory permits one also to solve the following partial problem of great practical significance: to determine the velocities of propagation of elastic waves in sufficiently small blocks of materials of the order of centimeters in length (particularly in samples of minerals), which possess an arbitrary shape. The possibility of such measurements is the great advantage of methods which utilize the impulse regime of oscillations, in comparison with methods which utilize a static load or stationary oscillations and which require for the measurement of velocities in samples that the correct geometrical form be preassigned to these samples. It can be assumed that the indicated arrangement will find extensive application both in the various branches of industry where seismic methods are employed and also in institutions of higher learning which are preparing specialists in geophysical methods of prospecting.

The Laboratory for Modeling of Seismic Phenomena, Geophysics Institute, Academy of Sciences USSR, is also conducting experiments on the study of the mechanical processes which can occur in the zones of earthquake foci. These works constitute a part of the general program of investigations in the institute on clarifying the causes for the emergence of earthquakes and on finding the methods for forecasting them.

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